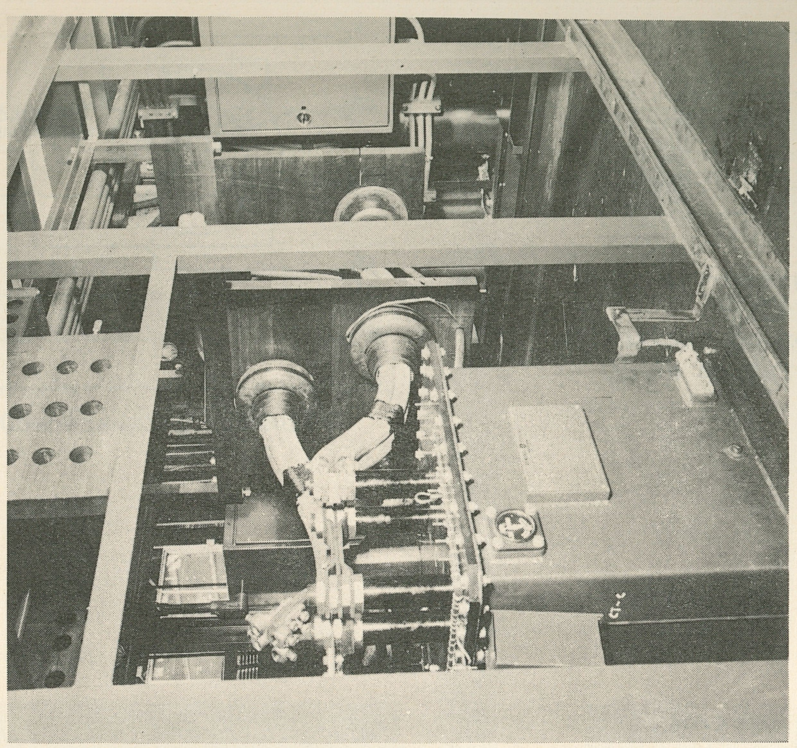

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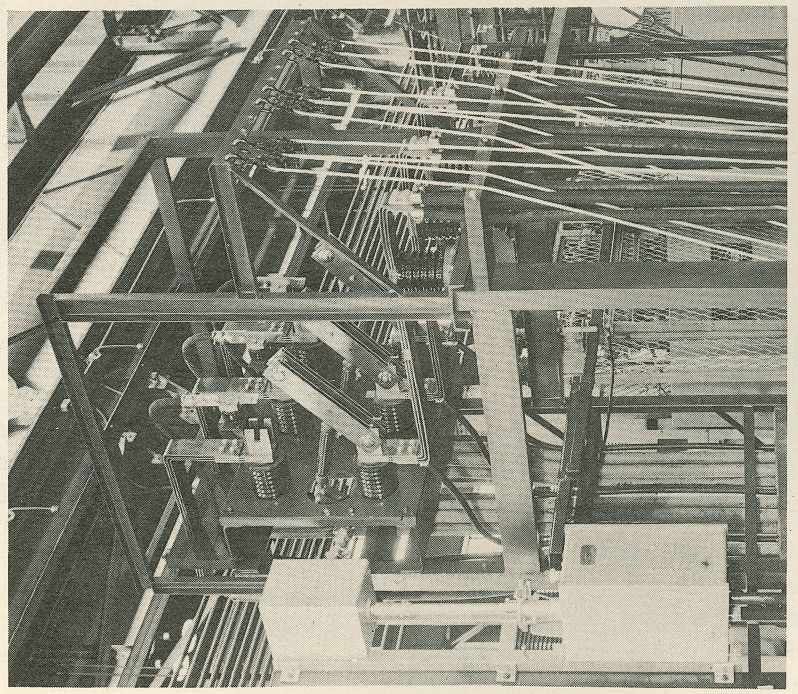

Fig. 11. Two position, interlocked, high voltage disconnect switch in service.

Mr. Kingsbury

District Conference Paper

ORTHOMAGNETIC CURRENT TRANSFORMERS FOR LABORATORY AND FACTORY TESTING

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A paper recommended by the AIEE Committee on Special Instruments and Auxiliary Apparatus for the AIEE North Eastern District Meeting, Pittsfield, Mass., May 1-3, 1957. Manuscript submitted February 1, 1957; made available for printing March 13, 1957.

Price: 40¢ To Members
80¢ To Nonmembers
(5¢ per copy additional if first class mailing desired)

Paper No. DP
57-530

ORTHOMAGNETIC CURRENT TRANSFORMERS FOR LABORATORY AND FACTORY TESTING

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Precision measurement of electrical energy is required to demonstrate the satisfactory performance of electrical apparatus in meeting standards and guarantees. Manufacturers of power apparatus must employ highly accurate methods of measurement in test; users likewise require equal precision if comparable checks on operating efficiency are to be made periodically.

Energy measurements at low power factors necessitate exact determination of the angle between voltage and current. Normally loss measurements on highly inductive apparatus require that correction factors be applied to the phase defect angle of the current transformers. Correction factors at best are approximations or interpolations and must be applied by skilled technicians, resulting in added cost and time.

Often the apparatus to be tested vary widely in current rating so that a number of current transformers with resultant primary switching are involved. Adaptation of the orthomagnetic principle(1) to a current transformer of variable ampere turns (tapped secondary) makes available in a single primary transformer, laboratory accuracy over a current range not found by other known means. The accuracy is such that it is not necessary to apply correction factors to the wattmeter readings. These advantages are being realized through the use of orthomagnetic transformers in the test departments of our Company.

The Problem of the Accuracy or Correction Factors

Conventional transformer performance characteristics are given by curves of ratios and phase angles, since these vary in value as the primary current varies from full load to fractional loads.

A constant ratio correction factor of course would be of little or no consequence, since this would involve only a fixed multiplier. The case of phase angle even if rendered constant is troublesome, because the ultimate correction to be made on the meter readings would differ for different power factors and power factors are normally different at different loads. The problem then is to make the percent ratio error at least constant (if not smaller) and the phase angle smaller (if not constant). The ratio and phase angle vary with load because the exciting current of the current transformer is not proportional to the load. If this proportionality was constant, the current transformer would have a single ratio correction factor and a single phase angle correction at all currents.

Since current transformers are operated at low densities, the deviation of the excitation curve from a straight line is not due to saturation but by just the opposite, that is, the increase in permeability with increasing density around the lower bend of the magnetization curve. See Fig. 1.

The results of this non-linearity are almost as objectionable as those of saturation with the difference that the relative errors are larger at the smaller loads instead of at the higher loads.

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In the final analysis, however, the errors of a current transformer are dependent upon the phase angle and the magnitude of its exciting current and the less this current the smaller are the resultant errors.

From the above it appears, therefore, that the errors associated with a current transformer can be materially reduced by the simultaneous actions of:

a) Straightening of the excitation curve
b) Reduction of the exciting current

These two objectives have been accomplished in the orthomagnetic current transformer.

The Orthomagnetic Principle

If a core is excited from an A-C source and then a higher frequency excitation superimposed on it through a separate winding of suitable design, maintaining the original excitation unchanged, it will be observed that the volt-amperes input by the original (lower frequency) circuit is diminished by the superimposition, although the total losses in the core may be considerably increased. To the lower frequency source, the iron behaves as an improved material; reduction of the exciting current to less than 50 percent of its original value without high frequency superimposition has been obtained. See Fig. 2.

That this improvement cannot be a matter of one circuit delivering power to the other circuit in the ordinary way will be appreciated by noticing that the two circuits (the high and low frequency sources) are designed with their mutual inductances balanced out, Fig. 3, so that the higher frequency cannot induce any current in the lower frequency circuit, and vice versa.

In addition to reducing the exciting current, a much more important result of the auxiliary high frequency excitation is that it makes the low frequency exciting current proportional to the primary current. A device incorporating a core of which the magnetization has been rendered straight by auxiliary high frequency excitation, has been termed orthomagnetic(1) (having straight line magnetic characteristics). By the superimposition of the additional high frequency excitation ratio errors are divided by more than 10 and phase angles by more than 60. With errors rendered constant, the phase angle error may be compensated by an auxiliary impedance and the ratio error by a tapped autotransformer between the secondary and burden.

The equipment to furnish the 180 cycle excitation to the current transformer is shown in Fig. 3 and consists of a wye-delta bank of three small single-phase transformers, with the corner of the delta opened for connection to the terminals A and B as a single-phase system, while the wye-winding is excited from a three-phase, 60 cycle source(2).

Electrical Circuit

Orthomagnetic current transformers discussed in this paper differ from bushing type current transformers previously described(3) by being complete with fully insulated primary winding and adjustment unit in a single tank. Also the adjustment equipment has been simplified to the minimum required for a moderate range of burdens. Even so, compensation for other burdens by readjustment is available if required. Thus the numerous switches, autotransformer taps and reactor are eliminated. The static frequency converter may, of course, be used, although a miniature motor-generator set has been employed in most applications.

The relative simplicity of these transformers is apparent in the schematic circuit diagram of Fig. 4. Three separate windings -- primary, secondary, and exciting (high frequency) windings are essential; a test winding is usually added as a fourth separate winding unless the turns in one rated section of the secondary are equal to the turns of the primary.

Sketched in Fig. 5 is the simplified compensation circuit consisting of an adjustment transformer and associated capacitor bank. The capacitive compensating load on one section of the secondary (normally the minimum full burden tap) suffices to correct the phase angle of all taps by balancing the power frequency component of the magnetizing current. Because the exciting current is linear, the compensation holds over a wide range of currents and fixed power factor burdens at a given frequency on all taps.

Residual ratio error is rendered insignificant by a few "series regulating" turns wound over the wound core adjustment transformer. The higher ampere turn taps do not normally require "regulating" turns.

Physical Construction

Arrangement of the various windings relative to the cores is represented in Fig. 6. Each core is wound with its evenly distributed exciting winding, assembled as a pair, and insulated as one.

The secondary winding is wound over the insulated exciting windings; it is distributed between taps to minimize secondary reactance. When a test winding is used, it is wound over the exciting windings.

High density crepe paper, the effectiveness of which was demonstrated in a low-liquid-content current transformer[4], is taped over the secondary winding where it conforms to the shape of the coil and, upon impregnation with the insulating liquid, provides a void-free insulating barrier.

A primary winding of crepe paper insulated cable is distributed around the circumference over the major insulation as shown in the photograph of Fig. 7. For currents of 2500 amperes or higher, "U"-shaped copper bars suspended from the terminals have been employed. The compensating unit is mounted under a hand hole in the cover where it is available for easy adjustment.

One modification utilizes a high current (1500 ampere) concentric bushing for use on a 75 Kv circuit. The concentric construction of the bushing permitted use of a small tank for the high test voltage required. Externally this transformer appears as in Fig. 8.

Accuracy Beyond Testing Standards

A knowledge of the excitation characteristics of the core permits calculation of ratio and phase angle errors at any burden. Burdens encountered in many metering applications are resistive of 20 VA or less.

Excitation characteristics at 60 cycles with and without triple frequency excitation are compared with mumetal in Fig. 9. The high frequency excitation reduces the exciting current to values well below those of mumetal even at the low densities where mumetal presents maximum permeability[5]. But of even greater significance is the linear relationship between excitation and induction. This permits what to all

practical purposes is the elimination of errors by compensating means previously described. It should be apparent, however, that errors without the compensation are less than those existing in commonly available current transformers.

Results of tests made on a transformer rated 100/50/25/15/10/5 to 5 amperes are presented in Table I. Errors at the lowest ratio of 5:5 (5% of the total turns) are less than 0.001 in ratio and 1 minute of phase angle over the current range of 10% to 150% of rated current at 60 cycles. No change in compensation was made during any of these tests.

Above the 15 ampere tap, errors are essentially zero in practical applications on resistive burdens below 25 volt amperes without compensating capacitor or adjustment turns. Only when the range is extended below 15 percent of the full ampere turns is the compensation required to reduce the small errors to negligible values.

One may observe that "absolute" accuracy of this order is unobtainable with Bureau of Standards[6] calibrated standard transformers. This is true, but the relative accuracy with respect to the slopes of the characteristic-curves is warranted, well within the sensitivity of the testing equipment, and consistent among the thousands of readings taken on over a hundred transformers.

At 25 cycles per second on an American Standards Association[7] burden B0.5, the phase angle errors presented in Table I are more positive than the 60 cycle errors, but even then are less than 2 minutes. The more positive errors result from the higher density at the lower frequency on the minimum tap and the fact that whereas the ratio compensation is good over a wide frequency range, the capacitive phase angle neutralizing current falls off at a different rate than the exciting current with decrease in frequency. By changing from the 60 cycle compensation to the optimum 25 cycle adjustment, even these small errors could be reduced.

The Effect of the Burden

Although practical applications have not required any appreciable change in burden, the effect of varying the burden is presumed of interest. Ratio correction factors and phase angles obtained on ASA burdens B0.5 and B2.0 are listed in Table II. At the 90% power factor B0.5 burden, the capacitive correction which was optimum on the resistive burden is not appreciably excessive. However, the overcompensation of the phase angle on the B2.0 burden is apparent at the 5:5 ratio. This could be corrected by reducing the capacitive compensation. Due to the reduction in capacitive compensating current on the higher ratios, this effect is negligible above the 15:5 ratio. Vector diagram of Fig. 10 indicates how the negative phase angle and greater than unity ratio correction factor occurs.

Ratio Range

In most laboratory and factory testing, a wide band of currents must be covered by the measuring equipment. Ordinarily, if this band is greater than two or three to one, a different ratio current transformer is necessary to obtain satisfactory meter readings. Thus, should the power current vary from 25 to 1000 amperes, a battery of approximately five current transformers would be required. High voltage switches, some of heavy current capacity, must be installed at high cost and added floor space.

A current range of this order of magnitude may be handled without primary switching by the orthomagnetic current transformer as described and at an accuracy on each ratio which eliminates correction factors. Errors less than 0.001 in ratio and 1 minute in phase angle are obtainable with approximately 300 ampere turns using a reasonable core section. For a given current transformer, this ampere turn value establishes the lowest current ratio. The upper current ratio is limited only by the size, cost, and short circuit capacity. One second over current factors of 10 to 12 times rating have given no difficulty with 6000 ampere turns, thus setting a reasonable maximum current ratio of twenty times the minimum secondary tap ratio.

Assuming minimum desirable current in the meters of 30 percent of full scale, currents having a range from approximately 60 to 1 (such as from 1.5 to 100 amperes, or from 90 to 6000 amperes) may be measured without corrections or primary switching. Extension beyond this range has been made as low as 0.75 ampere with an accuracy of 0.3 BO.5. A rated primary current range of 5 amperes to 3000 amperes is possible with primary switching between 100 and 250 amperes. In this case the necessity for providing a high current primary selector switch may be eliminated by designing the required visible safety interlocked disconnect (Fig. 11) for the test berth with two positions, 100 amperes and 3000 amperes. The safety device then serves as a selector switch. Fig. 12 shows an orthomagnetic current transformer rated 250/500/1500/3000 x 6000 : 5 amperes installed in a high voltage test berth.

Provision of additional or tapped primary windings makes it possible to construct a single transformer with a primary current range from 5 to 3000 amperes and higher. However, primary switching is required.

SUMMARY

The orthomagnetic current transformer provides a means of current measurement with an inherent accuracy beyond the calibration of transfer standards. Correction of readings is eliminated over a primary current range of approximately sixty to one on normal metering burdens without adjustment of compensation.

This wide current range may be metered without recourse to high voltage, heavy current primary switches.

With the exception of the 180 cycle excitation, these transformers are complete with simplified compensation in a single tank.

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ACKNOWLEDGMENT

The early work of J. W. Farr with transformers of this type is gratefully acknowledged.

TABLE I

All tests were made with the current transformer adjusted for optimum ratio and phase angle characteristics at a burden of 20 VA at 1.00 P.F.

Tests at 60 Cycles

Conn.	Bdn	Amps.	R.C.F.	Phase Angle Min.
5:5	20 VA @ 1.00 P.F.	0.5	1.0002	0
		1.0	1.0002	-0.4
		3.0	1.0002	-0.4
		5.0	1.0002	-0.5
		7.5	1.0002	-0.7
10:5		0.5	1.0000	0
		1.0	1.0000	-0.3
		3.0	1.0000	-0.3
		5.0	1.0000	-0.2
		7.5	1.0000	-0.2
15:5		0.5	1.0000	0
		1.0	1.0000	0
		3.0	1.0000	0
		5.0	1.0000	0
		7.5	0.9999	0
25:5		0.5	1.0000	-0.6
		1.0	1.0000	-0.4
		3.0	1.0000	-0.4
		5.0	1.0000	-0.3
		7.5	1.0000	-0.2
50:5		0.5	1.0000	-0.6
		1.0	1.0000	-0.5
		3.0	1.0000	-0.4
		5.0	1.0000	-0.3
		7.5	1.0000	-0.2
100:5		0.5	1.0000	-0.6
		1.0	1.0000	-0.5
		3.0	1.0000	-0.4
		5.0	1.0000	-0.4
		7.5	1.0000	-0.3

Tests at 25 Cycles

Conn.	Bdn	Amps.	R.C.F.	Phase Angle Min.
5:5	B-0.5	0.5	0.9998	+1.9
		5.0	0.9999	+1.8
10:5		0.5	0.9999	+0.2
		5.0	0.9999	+0.5
15:5		0.5	0.9999	0
		5.0	0.9999	+0.3
25:5	B-0.5	0.5	1.0000	-0.4
		5.0	1.0000	0
50:5		0.5	0.9999	-0.5
		5.0	0.9999	-0.2
100:5		0.5	0.9999	-0.6
		5.0	0.9999	-0.3

TABLE II

Tests made at Burdens B-0.5 and B-2.0 using same adjustment as for 20 VA @ 1.00 P.F.

Tests at 60 Cycles

Conn.	Bdn.	Amps.	R.C.F.	Phase Angle Min.
5:5	B-0.5	0.5	0.9993	-2.1
		5.0	0.9993	-2.3
	B-2.0	0.5	1.0010	-16.9
		5.0	1.0003	-20.0
10:5	B-0.5	0.5	0.9997	-0.9
		5.0	0.9998	-0.7
	B-2.0	0.5	1.0002	-4.6
		5.0	1.0001	-4.9
15:5	B-0.5	0.5	0.9998	-0.4
		5.0	0.9998	-0.2
	B-2.0	0.5	1.0000	-2.0
		5.0	1.0000	-2.1
25:5	B-0.5	0.5	1.0000	-0.8
		5.0	1.0000	-0.4
	B-2.0	0.5	1.0000	-1.2
		5.0	1.0000	-1.0
50:5	B-0.5	0.5	1.0000	-0.6
		5.0	1.0000	-0.4
	B-2.0	0.5	1.0000	-0.6
		5.0	1.0000	-0.5
100:5	B-0.5	0.5	1.0000	-0.7
		5.0	1.0000	-0.4
	B-2.0	0.5	1.0000	-0.8
		5.0	1.0000	-0.4

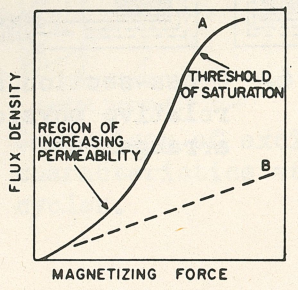


Fig. 1. Characteristic shape of magnetization curve for iron.

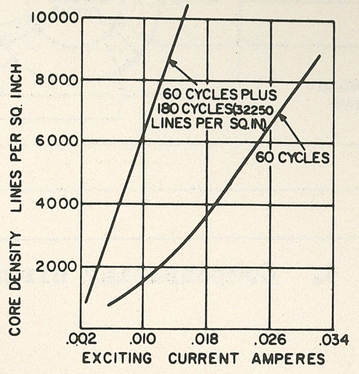


Fig. 2. Exciting current of wound core with and without triple frequency excitation.

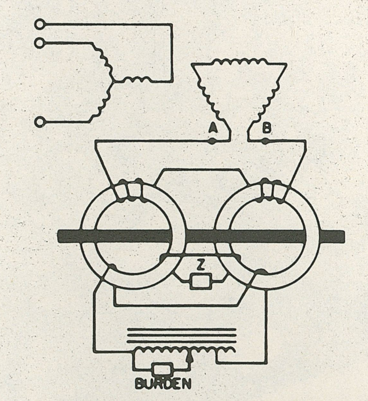


Fig. 3. Diagram of connections of a bushing-type current transformer with auxiliary triple frequency excitation.

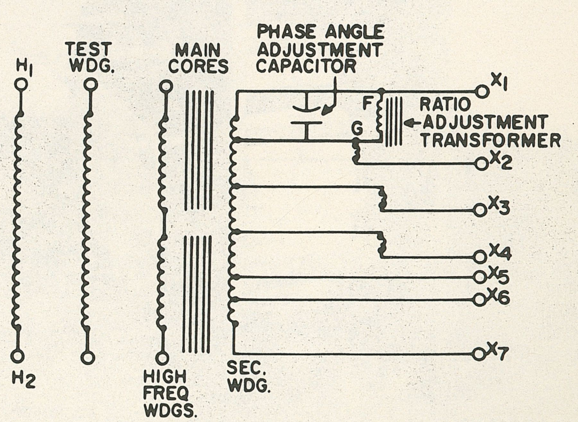


Fig. 4. Schematic circuit diagram.

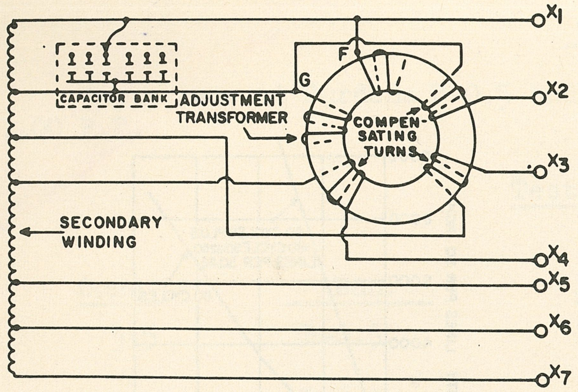


Fig. 5. Compensating circuit.

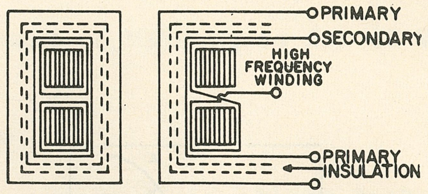


Fig. 6. Cross-section showing relative physical arrangement.

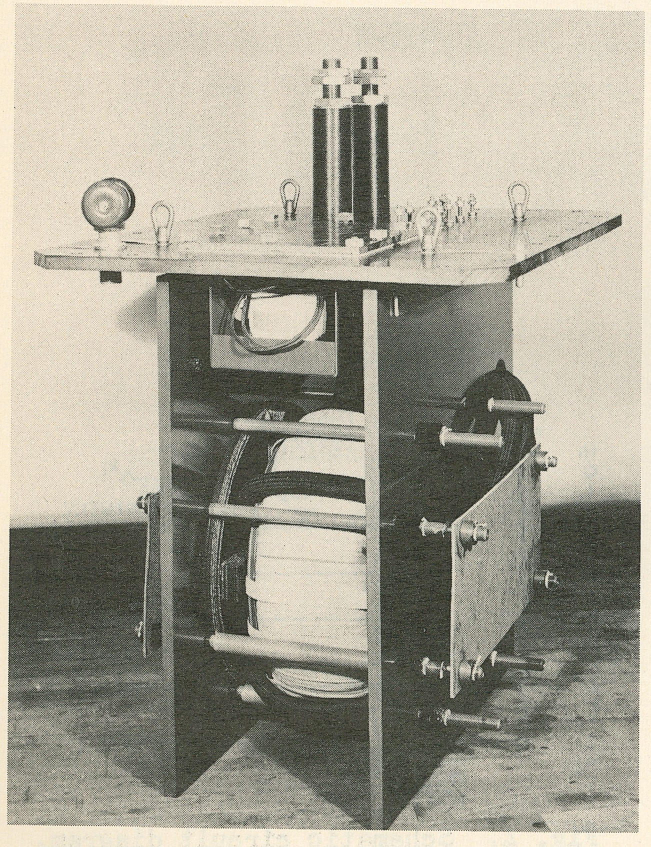


Fig. 7. Internal construction of liquid-filled orthomagnetic current transformer.

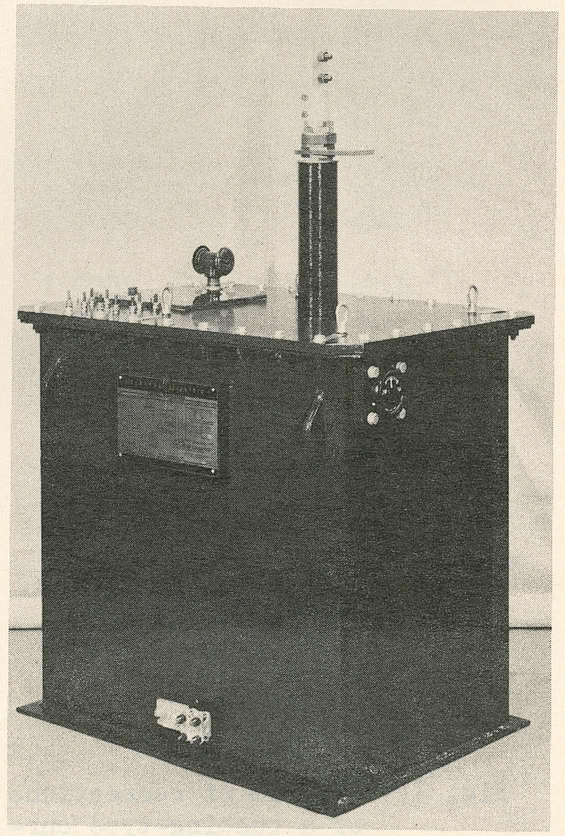


Fig. 8. Orthomagnetic current transformer with concentric bushing rated 1500/750/500/250:5 amperes for 75-KV circuit.

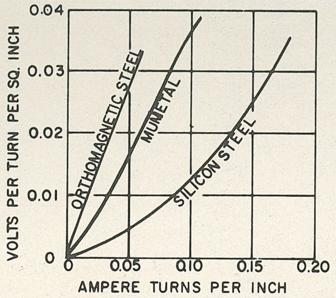


Fig. 9. Comparison of excitation characteristics at 60 cycles.

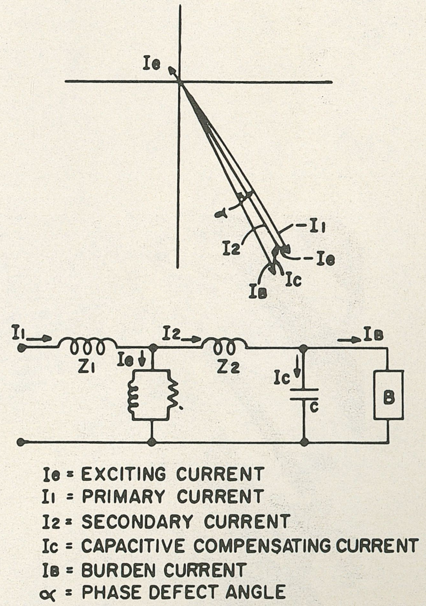
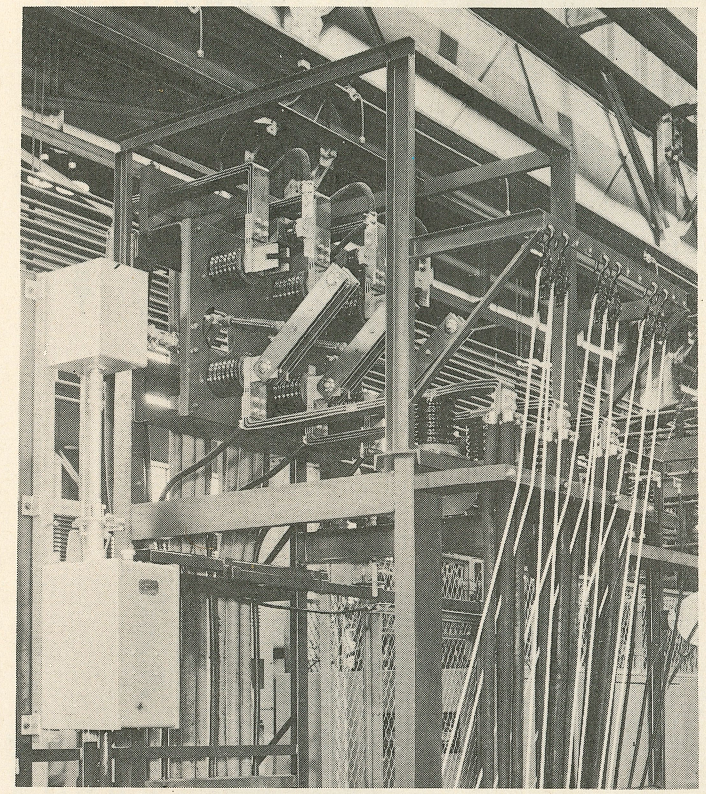


Fig. 10. Vector diagram and simplified equivalent circuit of compensated current transformer with excess capacitive current.



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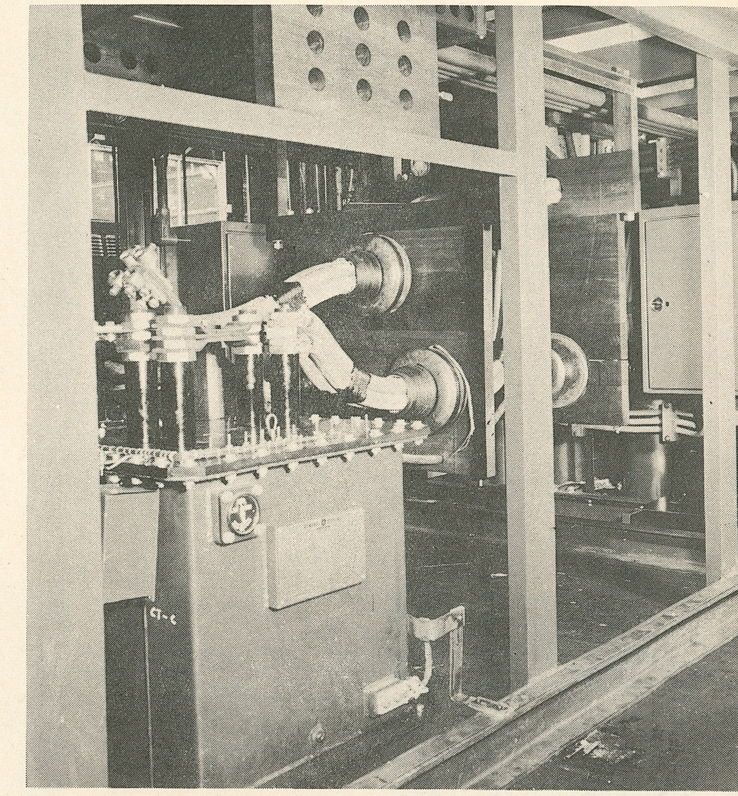

Fig. 12. Heavy current, series-multiple primary orthomagnetic current transformer installed in high voltage test berth.